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The role of marine reserves in achieving sustainable fisheries

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Many fishery management tools currently in use have conservation value. They are designed to maintain stocks of commercially important species above target levels. However, their limitations are evident from continuing declines in fish stocks throughout the world. We make the case that to reverse fishery declines, safeguard marine life and sustain ecosystem processes, extensive marine reserves that are off limits to fishing must become part of the management strategy. Marine reserves should be incorporated into modern fishery management because they can achieve many things that conventional tools cannot. Only complete and permanent protection from fishing can protect the most sensitive habitats and vulnerable species. Only reserves will allow the development of natural, extended age structures of target species, maintain their genetic variability and prevent deleterious evolutionary change from the effects of fishing. Species with natural age structures will sustain higher rates of reproduction and will be more resilient to environmental variability. Higher stock levels maintained by reserves will provide insurance against management failure, including risk-prone quota setting, provided the broader conservation role of reserves is firmly established and legislatively protected. Fishery management measures outside protected areas are necessary to complement the protection offered by marine reserves, but cannot substitute for it.

Keywords: marine protected area; fishery management; no-take zones; marine conservation

1. INTRODUCTION

In the last 15 years, there has been a revolution in our understanding of human impacts on the marine environment (Roberts 2003). From the 1960s to the 1980s, pollution was the primary focus for concern. The global fish catch was increasing and many people were optimistic that fishery expansion could feed the world's growing population. Today our view of the state of fisheries has radically altered as fish stocks across the world decline and collapse and global landings fall (Watson & Pauly 2001). We now view fishing as the longest standing and most serious of our influences on the oceans (Jackson *et al.* 2001).

The seas of today are very different from their pristine state. Stocks of large, predatory fishes are estimated to be less than a tenth of their unexploited biomass across large swaths of the world oceans (Myers & Worm 2003). Contrary to popular belief, marine species do not always recover from depletion. Forty percent of 25 stocks of commercially important fish examined by Hutchings (2000) failed to show any sign of recovery 15 years after their collapse. We now recognize that marine ecosystems are being shifted into less desirable alternative states that may become persistent. Lack of recovery of northern cod (*Gadus morhua*) in Canada, for example, could be due to increased relative predation rates on juvenile cod, and reduction in their forage species (Bundy 2001; Rose & O'Driscoll 2002).

We have long thought that marine species are unlikely to become extinct, but now realize that many are narrowly distributed and/or possess life-history characteristics that put them at high risk of complete disappearance (Roberts & Hawkins 1999; Carlton *et al.* 1999; Dulvy *et al.* 2002). As fisheries are depleted in shallow water, fishing penetrates deeper. The deep sea, that final bastion of the remote unknown, is no longer safe from harm (Roberts 2002).

Until recently, responsibility for managing the marine environment has rested largely in the hands of fishery managers. Conservation concerns have been secondary to economic imperatives, and marine conservation efforts have seriously lagged behind those on land. However, coastal nations of the world now see the urgent need to ramp up protection of the marine environment both to recover fisheries and safeguard biodiversity. At the World Summit on Sustainable Development in 2002, they agreed to establish national networks of marine protected areas by 2012, and to rebuild fish stocks to maximum sustainable yield levels by 2015. The scientific advisory body to the Convention on Biological Diversity (SBSTTA) recommended in 2003 that areas closed to all extractive use, here termed marine reserves, should form the core of national networks of marine protected areas. The World Parks Congress of 2003 recommended that 20–30% of every habitat in the sea should be given full protection from fishing.

Enthusiasm for fully protected marine reserves is strong because a growing body of theoretical and empirical work suggests they can simultaneously meet conservation and

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fishery management objectives. Within their boundaries, they protect animals and their habitats; beyond their boundaries, they can enhance surrounding fisheries by emigration of animals and export of their offspring (Murray *et al.* 1999; Roberts & Hawkins 2000; Russ 2002). Stocks of exploited species within reserves typically increase three to fivefold within 5–10 years of protection (reviewed in Gell & Roberts 2003*a*,*b*). In addition to recovering stocks of target species, other key fishery management benefits claimed for marine reserves include the development of natural age structures of exploited species, protection of genetic variability, restoration of ecosystem integrity, more predictable and often higher catches and insurance against management failure (Bohnsack 1996).

Many people remain sceptical that marine reserves can benefit fisheries, especially fishers and managers. They argue that we lack experience with marine reserves implemented at large scales and for long periods, particularly in temperate waters and in settings with industrial fisheries. Many question whether they are needed at all, suggesting that reducing fishing effort alone will be enough to achieve conservation and fishery management objectives. We build on a review of experience with marine reserves worldwide (Gell & Roberts 2003*a*,*b*) to explore their role in fisheries management. We first address concerns in the fishing industry and among fishery managers about the use of reserves. We then examine the strengths and limitations of present fishery management tools, including marine reserves, and identify ways in which these options can be used in combination to achieve sustainability. We conclude that large-scale marine reserves networks must be an integral element of fishery management if we are to achieve sustainable fisheries while maintaining marine biodiversity and ecosystem processes.

2. MYTHS ABOUT MARINE RESERVES

Some concerns about marine reserves are so frequently restated that they have taken on the mantle of mythology. These myths have arisen partly because scientific evidence has been insufficient to quash them and partly because the hyperbole of conservation advocacy has perhaps polarized fishing industry opinion against marine reserves. Scientific evidence on the effects of reserves has snowballed in recent years but some misperceptions still stubbornly remain.

(a) *Myth 1: marine reserves can replace other forms of fishery management*

Concerns about the impacts of fishing on juvenile fishes, on the food of fishes and on fish habitats were raised as early as the fourteenth century as fishers pleaded with their sovereign to restrict the use of the newly invented beam trawl (Alward 1932). Such worries were brushed aside then, as they have been many times since. The sea seemed limitless and there was always somewhere else to fish. In the mid-nineteenth century, this view was so strong that in 1866 a Royal Commission removed all restrictions on fishing (Johnstone 1905). Thomas Huxley, one of the commissioners, argued there was no evidence that people could reduce the abundance of fish and so regulations were an unnecessary impediment to commerce.

Some critics argue that today's proponents of marine reserves advocate a return to these times and that marine protected areas will do away with other restrictions on fishing. A sea in which havens for fishes are interspersed with open access zones that could be exploited using any kinds of gear would soon result in intense conflict among fishers and scorched-earth fishing below water. While some of the first marine reserves were designed for use in developing countries where there is often little capacity for fishery regulation (Alcala 1988), experience shows that they work best when implemented in association with other fishery management tools (Gell & Roberts 2003*a*). On Georges Bank, rebuilding of depleted groundfish stocks is being achieved with closed areas implemented alongside effort reduction (Murawski *et al.* 2000). Without effort reduction, stocks would be intensively overexploited outside reserves (New England Fishery Management Council 2004). In Chile, marine reserves are part of a co-management package that includes assigning exclusive fishing rights to communities, catch quotas and closed seasons (Castilla *et al.* 1998). The reserves protect large, productive animals from exploitation and promote higher biomass, while the other measures regulate take from the fishery. In South Africa, line-fish catches by recreational and commercial fishers are limited by legal sizes and bag limits (Cowley *et al.* 2002), but these measures are underpinned by reserves that have stabilized catches and prevented the fishery collapsing in the face of rising effort (Attwood 2002). Marine reserves are a powerful management tool, but work best if they are a supplement, not a substitute for other instruments.

(b) *Myth 2: marine reserves will have to be exceedingly large to work in temperate waters*

This myth is bound up with two others: that marine reserves are only effective in tropical or warm-temperate waters, and that they will not benefit migratory species. We have most experience of the effects of marine reserves in tropical and reef systems. In reef habitats, many species are relatively sedentary and so are afforded good protection even by relatively small protected areas (e.g. Roberts & Hawkins 1997; Babcock *et al.* 1999). Clearly, the more mobile a species is, the more often animals will stray across reserve boundaries into fishing grounds. While this 'spillover' represents one of the mechanisms by which reserves can enhance surrounding fisheries (reviewed by Gell & Roberts 2003*a*), excessive rates of movement will render the protective benefits of reserves ineffective (Kramer & Chapman 1999).

Species of fishes inhabiting continental shelf habitats in temperate waters tend to be more mobile than those living on reefs. In a briefing paper on applicability of marine reserves to temperate fisheries, the Fishery Society of the British Isles argued that to be effective, individual reserves would have to encompass regions larger than 60 000 km^2 (FSBI 2001). It would be extremely difficult to implement protected areas of this size in intensively used fishing grounds. For example, a single reserve of this size would cover *ca*. 20% of the North Sea. However, the paper ignored experience from similar habitats on Georges Bank in the Gulf of Maine where a variety of groundfish species are recovering following mobile gear closures of 4000–7000 km^2. These closures are equivalent to square protected areas with a perimeter of *ca*. 60–80 km (Murawsi *et al.* 2000; Gell & Roberts 2003*a*; Recchia *et al.* 2003) and would be feasible even in enclosed seas where space is limited.

Furthermore, strategically placed marine reserves can benefit migratory species through a variety of mechanisms, including improved habitat quality and feeding opportunities, greater survival of offspring, and protection at aggregation sites and migration bottlenecks (Apostolaki *et al.* 2002; Roberts & Sargant 2002; Norse *et al.* 2005). For example, protection of a spawning aggregation site for the hermaphroditic red hind grouper (*Epinephelus guttatus*) in the US Virgin Islands, representing just 1.5% of the fishing grounds, led to rapid increases in average fish size and a greater availability of males (Beets & Friedlander 1999; Bohnsack 2000).

Subdivision of the area to be protected into different reserves is necessary to benefit migratory species. It is also necessary to meet goals of biodiversity representation and replication of habitats in different reserves (Turpie *et al.* 2000; Roberts *et al.* 2003*a*,*b*). Placing all our conservation capital into a few very large reserves would not secure representatives of the full spectrum of biodiversity, nor would it be socially or politically feasible. In addition, while reserves must be large enough to afford protection to species, if they are too large, fishery benefits through spillover and export of offspring will diminish (Botsford *et al.* 2001). If reserves were designed with sufficient habitat representation and levels of replication to protect biodiversity, then dispersed network designs would arise by default. Such configurations would simultaneously benefit both fishery management and conservation.

Evidence for the efficacy of marine reserves has now expanded to encompass many habitats and geographical regions, including temperate waters (Gell & Roberts 2003*a*,*b*). On Georges Bank, for example, abundance and size of commercially important species have increased, age structures are expanding, and habitats are becoming more complex and diverse (Murawski *et al.* 2000; NEFSC 2001; NRC 2002; New England Fishery Management Council 2004). This clearly shows that marine reserves can play an important role in managing temperate industrial fisheries. However, marine reserves should be used as only part of the management package since mobile species and their habitats also require additional forms of management.

(c) *Myth 3: fishing-the-line will wipe out fishery benefits from marine reserves*

Fishing-the-line is the concentration of fishing effort close to marine reserve boundaries. It is a response to spillover of animals from protected areas and has been described from over a dozen countries (Gell & Roberts 2003*a*). In Scotland, for example, an 11 km^2 naval equipment testing area had been closed to fishing for around 20 years when Grattan-Cooper (1996) said that 'the best fishing and the largest prawns are to be found around the perimeter of the [protected area]. So much so that it is regularly reported that the cruciform shape of the [protected area] is picked out on the radar screen by fishing boat contacts'.

To some in the fishing industry, fishing-the-line is seen as a problem because it could prevent the supply of fisheries further afield. While intensive fishing-the-line may lead to most of the animals leaving protected areas being caught nearby, it causes more of a problem in allocation rather than yield. Animals moving from protected areas will supplement catches whether they are caught close to reserves or farther away. Consequently, fishers living near reserves stand to gain more from spillover than those further away. However, if marine reserves are distributed in networks throughout fishing grounds, all fishers would stand to benefit from protected areas.

Emigration of adult and juvenile animals is only one mechanism by which fisheries can benefit from protected areas; the other is export of eggs and larvae via ocean currents. Our views of the scale of such planktonic dispersal are changing as evidence grows that larvae rarely drift passively with currents. It appears that many behave in ways that increase their chances of local retention (Mora & Sale 2002). Nevertheless, genetic evidence and advancing fronts of introduced species suggest that dispersal can commonly reach distances of several tens of kilometres (Grantham *et al.* 2003; Shanks *et al.* 2003). With larval dispersal leap-frogging vessels fishing-the-line, reserves are able to supply more distant fisheries.

(d) *Myth 4: redirecting fishing effort from protected areas will do more harm than good*

Kaiser (2003) calls for caution in the use of closed areas in trawled and dredged systems. He contends that under normal circumstances, fishers' behaviour leads to a patchy distribution of fishing effort with some areas being heavily trawled, and others rarely disturbed. Imposing closed areas on fishing grounds will, he suggests, lead to some of the displaced fishing effort being expended on areas not usually fished, so possibly doing more harm than good. Others have used similar arguments against protecting spawning aggregations, suggesting that this would displace effort onto more vulnerable sites and life stages (Horwood *et al.* 1998). A third argument is that intensified fishing effort close to reserves from fishing-the-line will cause excessive habitat damage, especially by trawls and dredges.

While these arguments have merit, they do not warrant abandoning the concept of marine reserves but simply point to the fact that sites for protected areas should be chosen with care. For example, areas of known vulnerability should have priority for protection. If Kaiser (2003) is correct, and fishers do adhere to favoured areas, then knowledge of fishing patterns could be used to advantage in choosing where to protect. Areas avoided by fishers could indicate places with less impacted habitat. Such places could contribute much to maintaining good examples of habitat that may form important juvenile habitats and feeding areas for commercial species. However, if they were little fished to begin with they would contribute less to rebuilding targets for exploited species. Data on the distribution of fishing effort, coupled with habitat data, could be used to select candidate areas for protection. Using habitat features which reduce fishing efficiency, such as high relief areas which damage gear ('trawl hangs') is an allied approach to identifying sites for protection (Link & Demarest 2003). Closing such areas would benefit fishers by helping them to avoid expensive losses and gear repairs and would help fish populations by protecting juveniles of commercial fish species.

The expectation that fishing-the-line will develop around successful marine reserves highlights the need for careful design. In placing boundaries, we should avoid areas with sensitive or vulnerable habitats that will be damaged by intensive fishing. Where this is not possible,

Table 1. Common fishery management tools and their uses and limitations in delivering sustainable fisheries and conservation. (Measures shown are listed in approximate order of conservation value, increasing from top to bottom.)

management tool	values	limitations
total allowable catch quotas	although intended to maintain stocks at or above desired target levels and deliver sustainable fisheries, quotas have many drawbacks and few advantages	species-specific have high information requirements do not consider problems of bycatch, discarding, habitat damage by fishing gears, or threats to particular species fail to protect genetic or population structure of stocks
precautionary total allowable catch quotas	precautionary quotas recognize that stock assessments are often unreliable and control of fishing effort is imprecise reduce the likelihood of overshooting sustainable catch levels	species-specific high information requirements do not consider problems of bycatch, discarding, habitat damage by fishing gears, or threats to particular species fail to protect genetic or population structure of stocks
mesh size restrictions	designed to protect young fishes from capture	gears can be towed in ways that close up mesh ineffective when net is full where the same gear captures a wide size range of species, mesh size limits are compromises between protection and production setting sizes appropriate for the largest species will sacrifice productivity of small species bycatch remains a problem
square mesh panels	designed to protect young fishes from capture and to improve escape of undersized fishes	do not work as well when net is full gears can be towed in ways that reduce escape of undersized fishes
bycatch quotas	impose limits on landings for one species based on quotas for bycatch of another/others encourage design and use of gears or fishing methods that minimize bycatch	require 100% observer coverage on boats to be effectively implemented without this kind of enforcement, the measure encourages dumping of bycatch catches of target species may be held below sustainable levels
minimum or maximum landing size for fish	minimum landing sizes seek to prevent capture of immature animals and avoid growth overfishing maximum landing sizes seek to retain larger older animals for their contribution to reproduction	do not prevent other sizes of target species being caught and discarded, possibly with significant mortality do not prevent bycatch of non-target species costly to police
gear modifications to reduce bycatch or habitat damage	designed to reduce collateral damage done by fishing, particularly to non-target species can improve efficiency of catch processing and marketability of catch	most gear modifications reduce catch efficiency so that fishers will not use less damaging gears unless required to do so by law there are practical limits to damage limitation or bycatch reduction gears cannot be designed that can selectively catch species that have similar morphology, behaviour and habitat use
limited entry or vessel retirement schemes	designed to limit numbers of vessels in fishery and so reduce fishing effort to desired levels	remaining vessels can be upgraded to increase fishing power vessels can be operated round the clock by multiple crews does not restrict where vessels can operate reductions in fishing effort spread over the entire fishery will be insufficient for recovery and protection of many species and habitats
limitations on time spent fishing	designed to reduce fishing effort	seasonal closures can lead to 'derby fisheries' where effort is concentrated into short periods risking the safety of fishers and flooding the market, driving down prices

	unlike restrictions on landings, this measure aims to prevent animals being caught at all, rather than caught then discarded, as is often the case with catch limits	fishers also have an incentive to increase the fishing power of vessels to maximize catch 'days-at-sea' restrictions avoid the problem of flooding markets, but share the other drawbacks
spatial restrictions on gear use	designed to reduce conflicts among sectors of the fishing industry (e.g. users of fixed and mobile gears) and to protect areas where species or habitats are especially vulnerable to harm from particular gears have considerable conservation potential but are usually implemented only to achieve narrow fishery goals	many species remain vulnerable to capture by permitted gears could redirect fishing effort to other areas
outright gear prohibitions	designed to eliminate use of unsustainable or highly damaging fishing methods	regulators may be reluctant to ban gears outright because of capital already invested by the fishing industry
seasonal closed areas	designed to protect aggregations of target species when they are particularly susceptible to overfishing or disturbance can be a highly effective means of reducing fishing mortality and/or increasing spawning success	usually species-specific could redirect fishing to other areas species may be susceptible to increased fishing effort at other times and places
fully protected marine reserves	designed to protect and restore ecosystem integrity, recover populations of target species, allow them to develop extended, natural age structures, protect genetic variability, produce more predictable catches and provide insurance against management failure provides a high level of conservation benefit beyond values to fisheries	some mobile species may remain vulnerable outside protected areas could redirect fishing to other areas

buffer zones could be implemented around reserves in which only the use of static fishing gears is permitted. Such zones have been successful in reducing conflicts among fishers using fixed and mobile gears (e.g. Kaiser *et al.* 2000). Buffers around reserves would provide a more gradual transition between fully protected areas and regions swept by mobile gears, helping to reduce concentration of effort by fishers using the most damaging fishing methods (Morgan & Chuenpadgee 2003).

(e) *Myth 5: marine reserves will put fishers out of business*

Concerns about fisheries being shut down are allied to Myths two and four. Marine reserves will displace some fishers from parts of their former fishing grounds and implementing extremely large marine reserves could create considerable difficulties. However, as noted above, protected areas of 4000–7000 km^2 have benefited mobile species characteristic of temperate industrial fisheries. Protected areas of this size would be very unlikely to cause significant access problems for distant water fleets operating far from home ports. By contrast, blocking off similar-sized sections of coastline as no-take zones would cause much hardship for near-shore fleets with limited mobility. They would not be feasible, nor would they be desirable.

Marine reserves need to be scaled appropriately for the species, habitats and fisheries they are designed to support. In coastal areas, marine reserves of a few to a few tens of square kilometres have proven effective in recovering stocks and habitats (Cote *et al.* 2001; Halpern 2003; Gell & Roberts 2003*a*). The same overall fishery support function can be achieved using smaller, more numerous protected areas that attain similar overall coverage to fewer, larger reserves in offshore regions (Hastings & Botsford 2003; Roberts *et al.* 2003*a*). In this respect, fishery and conservation roles of reserves are again compatible. Smaller, more numerous reserves will spread fishery benefits more widely, and enable continued access to fishing grounds for all. Applying principles of habitat representation and replication will result in smaller, more numerous reserves in places where habitats are more patchy, i.e. coasts, compared to places where they are more extensive and uniform, i.e. offshore regions.

3. COMPLEMENTARITY OF RESERVES AND OTHER TOOLS

Following the Royal Commission of 1866, Thomas Huxley's vision of freedom to fish prevailed largely unimpeded until the turn of the twentieth century. However, by this time, Britain's waters were full of steam trawlers and evidence of overfishing was unimpeachable (Johnstone 1905). A series of restrictions were introduced that have been steadily added to since. Despite good intentions, limits on fishing have never kept pace with the effort, skill and ingenuity of fishers. Since 1900, stocks of the main demersal fishery species of northern Europe have declined by 80–90% (Christensen *et al.* 2003). Today, we face the stark prospect of a total moratorium on fishing for some of the prime species that have satisfied tastes in seafood for centuries (see www.ices.dk). We have arrived at this point because all regulations can be undermined to some extent by ever-resourceful fishers, or by decision-makers whose good intentions are ultimately misguided.

4. MARINE RESERVES AND CONVENTIONAL MANAGEMENT TOOLS COMPARED

Table 1 describes the advantages and limitations of many of the tools available to fishery managers. Most fishery management tools are designed to limit catches to some fraction of estimated target stock sizes. They do this either through gear design or limits on the places people can fish and the time spent fishing. In this sense, most tools have conservation value too, if they achieve their intended goals.

Botsford *et al.* (2003) contrasted the effects of reserves with conventional tools and drew two conclusions: (i) that the effect of reserves on catches is similar to reducing fishing effort and (ii) that their effect on yield-per-recruit was similar to increasing the age at first capture. Marine reserves can thus be seen as a different means of achieving the core goals of fishery management. However, the outcome of the use of reserves is qualitatively different from that of conventional tools. Reserves represent an extension of spatial tools for restricting fishing, broadening the scope of protection from one or a few species to many and from limited-time to full-time protection. They deliver benefits in a spatially defined manner, extending age structures of stocks greatly in some places and little or not at all in others. They reduce fishing effort to zero in some places, but may increase it in others. Marine reserves have limitations in the degree to which they protect species. Reserves thus provide important, but only partial protection to stocks and therefore need to be complemented by other management measures in areas remaining open to exploitation.

Reserves have other limitations. While sedentary species will gain full protection within reserves, the degree of protection will decline as mobility increases. For highly mobile species, reserves can provide important protection in places and at times of vulnerability and can improve feeding and survival opportunities. However, conventional management tools must deliver much of the protection these species need. For sedentary species, marine reserves can conceivably provide the bulk of protection, although constraints on reserve placement will necessitate the application of other controls in most cases.

In general, reserves complement, but do not conflict with, the great majority of existing management tools. The only possible area of conflict might be for a handful of fisheries where management is based on pulse fishing seasonal aggregations. Protection of aggregation areas would prevent application of this tool.

5. LIMITATIONS OF CONVENTIONAL MANAGEMENT TOOLS

Conventional management tools have limitations that undermine their ability to secure the intended benefits. Virtually every conventional fishery management tool can be legally circumvented, by changing either gears or fishing practice. For example, mesh size restrictions on trawl nets can be undermined by towing in certain ways and become ineffective when nets are full. Limitations on days at sea can be overcome by increasing fishing power—larger nets, more hooks and faster tows. In their efforts to remain one step ahead of fishers, managers have implemented ever-more complex combinations of restrictions that have only slowed rather than reversed declines.

Other forces also undermine existing management measures. Different fisheries are often managed by different committees that may communicate poorly with one another, even though their target species have important interactions in the wild. Fisheries for a species managed by one committee, for example, may cause collateral impacts on the target species of a different committee through bycatch and discards. Calls for ecosystem approaches to fishery management are being received favourably today, but in practice, management remains fragmented, undermining its ability to deliver success.

Politicians or other executors of scientific advice often exacerbate management difficulties by setting more generous catch limits than recommended. In Europe, for example, fishery ministers have the final say on quotas and usually set total allowable catches 15–30% higher than their advisors recommend (see ICES reports at www.ices.dk/committe/acfm/comwork/report/asp/ACFMRep.asp). Such decisions are made in good faith to reduce the impacts of quota reductions on fishing communities but in reality, they condemn the industry to failure in the long-term. The company executive who refused to cut costs in order to spare the workforce would ultimately be condemned by workers and shareholders alike when the business eventually collapsed.

6. THE ROLE OF MARINE RESERVES IN MODERN FISHERY MANAGEMENT

Marine reserves and conventional tools have many common goals but reserves should be integrated into the fishery management toolkit because they can achieve things that other tools cannot. There is no legal means of fishing in a marine reserve, so there is no lawful way of undermining the protection they afford to species and habitats. There is no surer way of integrating ecosystem level concerns into fishery management than protecting entire, intact ecosystems. Short of changing human nature, existing management tools offer few options for mitigating risky decision-making where the final choices on catches lie with politicians or industry representatives (Okey 2003). In the remainder of this paper, we explore how marine reserves can complement other fishery management tools in order to deliver sustainable fisheries and meet conservation objectives.

Effective nature conservation in the sea cannot be delivered without marine reserves. Only they can protect habitats that recover from impacts over very long timescales and only complete protection will provide sufficient refuge for highly vulnerable species. Examples of vulnerable habitats in temperate waters include biogenic maerl beds (Hall-Spencer & Moore 2000), horse mussel (*Modiolus modiolus*) beds and deepwater reefs (Hall-Spencer *et al.* 2001; Fossa *et al.* 2002). Fishing impacts on these habitats are so severe that the case is compelling for their complete protection. For example, maerl beds are biologically rich communities based around slow-growing coralline algae. They take centuries to develop but are quickly destroyed by mobile fishing gears (Hall-Spencer & Moore 2000; Barbera *et al.* 2003). This means that any maerl beds left open to mobile fishing gears will be destroyed. A similar argument has been made justifying protecting all deepwater habitats from fishing (Roberts 2002).

By contrast, it may still be possible to fish sensitive habitats with static gears without threatening their integrity. However, some species are highly vulnerable to fishing, such as the common skate *Dipturus batis* (Dulvy *et al.* 2002). To afford them adequate protection would impose unacceptable reductions in effort on more resilient species with which they co-occur. Spatial protection in marine reserves offers a means of maintaining populations of vulnerable species without shutting down fishing altogether. This strategy is especially attractive given the potential of protected areas to support surrounding fisheries.

Marine reserves and fishery closures can likewise protect known points of vulnerability of stocks at specific places and times without preventing fishing elsewhere. For example, in most countries, herring (*Clupea harengus*) are protected while spawning in coastal areas. Short-term temporal protection of this kind is critical to avoid excessive fishing mortality and to protect newly spawned eggs. Such places could be considered for permanent protection to afford the full suite of reserve benefits for habitats and vulnerable species by preventing all habitat damage and affording complete refuges from fishing.

Fishery managers have not traditionally thought about habitat protection. Few of the models underpinning management include any terms relating to habitat, instead simply assume that habitats will support production. It is becoming evident that part of the reason for stock declines is that we are using fishing methods that damage, degrade and destroy essential fish habitat (Morgan & Chuenpadgee 2003). This collateral damage from fishing can increase natural mortality rates of fishes, slow growth and reduce reproductive success (Roberts & Sargant 2002). Marine reserves can protect the structural integrity and productivity of habitats important to fishery species thereby helping sustain fisheries (Collie *et al.* 1997; Auster & Langton 1999).

Fisheries curtail the age structures of fish stocks and leave few reproductively active year classes. Measures such as mesh size restrictions are used to allow mature individuals to escape but these are usually set at the lower size margins of maturity. As smaller fish produce far fewer offspring than larger animals, removing the largest age classes has a disproportionately big impact on stock reproductive output (Sadovy 1996). Continued take of the largest animals imposes intense selective pressure for earlier reproduction at smaller body sizes, which exacerbates the impact of curtailed age structures (Stokes & Law 2000). For example, stocks of North Sea plaice (*Pleuronectes platessa*) now mature at only half the size they did 50 years ago (Grift *et al.* 2003). While changes in gear selectivity can reduce some adverse selection pressures, no fishery management tool other than marine reserves can foster the full development of natural, extended age structures of fish species. Reserves will thus counter many of the undesirable evolutionary effects of fishing, helping prevent the loss of desirable traits (Trexler & Travis 2000). Extended population age structures provide resilience in the face of environmental uncertainty. They allow populations to persist through periods of unfavourable environmental conditions when survival of offspring is low.

Environmental variability also makes it difficult for managers to maintain stocks above target levels. Unexpected decreases in reproductive success or increases in natural mortality can undermine management measures set under

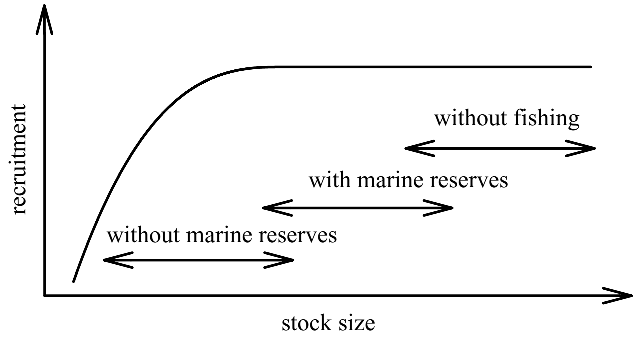

Figure 1. Beverton–Holt style stock-recruitment relationship showing the range of variation in stock sizes in an unfished system, in a system with marine reserves and in a system where there are no refuges from exploitation. Marine reserves can help sustain maximal levels of recruitment by keeping stock sizes above levels at which recruitment limitation occurs. Theoretical work suggests that this mechanism leads to more stable and predictable catches.

more favourable conditions (Rodwell & Roberts 2004). By providing spatial refuges from fishing, reserves help sustain stock levels (figure 1). For the same reason, reserves can also buffer catches against background environmental variability. A number of models of marine reserves suggest they will reduce year-to-year variation in catch size (e.g. Sladek Nowlis & Roberts 1999; Rodwell *et al.* 2002). Figure 1 shows the underlying mechanism for this effect. Reserves can prevent stocks falling below levels at which recruitment limitation occurs, and so help secure sufficient reproduction to maintain maximal replenishment rates.

Spatial closures have long been available to fishery managers as a means of protecting vulnerable life stages of species and reducing conflicts among fishery sectors. As early as the 1890s, large areas of Britain's territorial sea were closed to trawling to protect juvenile fishes and reduce conflicts between trawlers and line fishers (McIntosh 1899). Allowing vessels to continue fishing can seriously undermine the value of spatial closures, such as the 'plaice box' off the Dutch coast (Pastoors *et al.* 2000). Full protection from fishing is a more certain way of protecting juvenile fishes and their habitats than simply limiting the size of the boats allowed to fish a region. Stocks of key fishery species in Europe, such as cod (*Merluccius merluccius*) and hake, need not have continued declining if juveniles had been protected from bycatch, since several excellent episodes of reproduction occurred while adult stocks fell. Integrating marine reserves into the management portfolio could have provided the necessary protection.

Marine reserves are a tool with low information requirements, which once implemented, allow effective stock protection for species with a broad range of life-history characteristics. The first reserves implemented for fishery management reasons were designed to support catches in places with complex, multi-species fisheries, where relatively non-selective fishing methods are used, where resources for management are limited, and where regulatory powers are weak (Alcala 1988). Many fisheries throughout the world, including temperate industrial fisheries display these characteristics. The conservation values of marine reserves are universal—even blue-water pelagic habitats can benefit from protection from fishing (Norse *et al.* 2005). We have now learned enough about marine reserves to know they have value for fisheries across the globe, regardless of geographical, political or management setting (Gell & Roberts 2003*b*).

Finally, marine reserves can safeguard against management failure and within this we include the setting of over-generous, risky quotas by decision-makers. By protecting some fraction of stocks from exploitation, they may be able to prevent stock collapses that would be inevitable if there were only conventional checks on catches. To provide this insurance, the nature conservation role of reserves must be firmly established and legislatively protected. This will require close collaboration between fishery management, conservation parties and fishers in declaring marine reserves. Removal of marine reserves should only be undertaken with the consent of all.

7. CONCLUSIONS

Many fishery management tools now in use have conservation value. They are designed to sustain populations of commercially important species above certain target levels. However, their limitations are evident from our continued inability to stem the decline of the species they are designed to protect. For example, the tool of choice for managing fisheries in Europe, total allowable catches and national quotas, has the least conservation value of any management tool available (table 1) and has failed to deliver sustainable fisheries in the past. Due to the inherent limitations of the approach and the framework within which quotas are implemented within Europe, they will also fail to do so in the future. To achieve sustainable fisheries and protect non-target species and their habitats, fishery management must embrace tools that include prohibition of the most damaging gears, areas closed to particular gears, precautionary quotas, bycatch quotas, and modification of fishing gears and practices to reduce the collateral damage of fishing. Such measures will not, in themselves, be enough without the widespread introduction of fully protected marine reserves. Extensive networks of reserves will meet the stock protection needs of fishery managers and assure that conservation objectives are met (Gell & Roberts 2003*a*,*b*). Only when we add this tool to fishery management strategies will conservation and fishery goals become completely allied.

At the World Summit on Sustainable Development in 2002, the international community committed to rebuilding fish stocks to their maximum sustainable yield levels by 2015. Building towards the protection of a significant proportion of their habitat as a refuge from exploitation and collateral damage from other fisheries is the only certain way to recover stocks of overexploited species such as cod, whiting (*Merlangus merlangus*), scallops (*Pecten maximus*), hake, or skate (*Dipturus spp.*). Fishery management measures outside protected areas are necessary to complement protection offered by marine reserves, but cannot substitute for it.

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REFERENCES

Alcala, A. C. 1988 Effects of marine reserves on coral fish abundances and yields of Philippine coral reefs. *Ambio* **17**, 194–199.

Alward, G. L. 1932 *The sea fisheries of Great Britain and Ireland*. Grimsby: Albert Gait.

Apostolaki, P., Milner-Gulland, E. J., McAllister, M. K. & Kirkwood, G. P. 2002 Modelling the effects of establishing a marine reserve for mobile fish species. *Can. J. Fish. Aquat. Sci.* **59**, 405–415.

Attwood, C. G. 2002 Spatial and temporal dynamics of an exploited reef-fish population. PhD Thesis, University of Cape Town, South Africa.

Auster, P. J. & Langton, R. W. 1999 The effects of fishing on fish habitat. *Am. Fish. Soc. Symp.* **22**, 150–187.

Babcock, R. C., Kelly, S., Shears, N. T., Walker, J. W. & Willis, T. J. 1999 Changes in community structure in temperate marine reserves. *Mar. Ecol. Prog. Ser.* **189**, 125–134.

Barbera, C.(and 17 others) 2003 Conservation and management of northeast Atlantic and Mediterranean maerl beds. *Aquat. Conserv. Mar. Freshwat. Ecosyst.* **13**, 65–76.

Beets, J. & Friedlander, A. 1999 Evaluation of a conservation strategy: a spawning aggregation closure for red hind, *Epinephelus guttatus*, in the US Virgin Islands. *Environ. Biol. Fish.* **55**, 91–98.

Bohnsack, J. A. 1996 Maintenance and recovery of reef fishery productivity. In *Reef fisheries* (ed. N. V. C. Polunin & C. M. Roberts), pp. 283–313. London: Chapman & Hall.

Bohnsack, J. A. 2000 A comparison of the short-term impacts of no-take marine reserves and minimum size limits. *Bull. Mar. Sci.* **66**, 635–650.

Botsford, L. W., Hastings, A. & Gaines, S. D. 2001 Dependence of sustainability on the configuration of marine reserves and larval dispersal distance. *Ecol. Lett.* **4**, 144–150.

Botsford, L. W., Micheli, F. & Hastings, A. 2003 Principles for the design of marine reserves. *Ecol. Applic.* **13**, S25–S31.

Bundy, A. 2001 Fishing on ecosystems: the interplay of fishing and predation in Newfoundland-Labrador. *Can. J. Fish. Aquat. Sci.* **58**, 1153–1167.

Carlton, J. T., Geller, J. B., Reaka-Kudla, M. L. & Norse, E. A. 1999 Historical extinctions in the sea. *A. Rev. Ecol. Syst.* **30**, 515–538.

Castilla, J. C., Manríquez, P., Alvarado, J., Rosson, A., Pino, C., Espoz, C., Soto, R., Oliva, D. & Defeo, O. 1998 Artisanal 'caletas' as units of production and co-managers of benthic invertebrates in Chile. In *Proc. North Pacific Symp. on Invertebrate Stock Assessment and Management* (ed. G. S. Jamieson & A. Campbell) pp. 407–413. Canadian Special Publication in Fisheries and Aquatic Sciences 125. Ottowa: National Research Council Press.

Christensen, V., Guénette, S., Heymans, J. J., Walters, C. J., Watson, R., Zeller, D. & Pauly, D. 2003 Hundred-year decline of North Atlantic predatory fishes. *Fish and Fisheries* **4**, 1–24.

Collie, J. S., Escanero, G. A. & Valentine, P. C. 1997 Effects of bottom fishing on the benthic megafauna of Georges Bank. *Mar. Ecol. Prog. Ser.* **155**, 159–172.

Cote, I. M., Mosquiera, I. & Reynolds, J. D. 2001 Effects of marine reserve characteristics on the protection of fish populations: a meta-analysis. *J. Fish Biol. A* **51**, 178–189.

Cowley, P. D., Brouwer, S. L. & Tilney, R. L. 2002 The role of the Tsitsikamma National Park in the management of four shore-angling fish along the south-eastern Cape coast of South Africa. *S. Afr. J. Mar. Sci.* **24**, 27–35.

Dulvy, N. K., Sadovy, Y. & Reynolds, J. D. 2002 Extinction vulnerability in marine populations. *Fish Fish.* **3**, 1–40.

Fossa, J. H., Mortensen, P. B. & Furevik, D. M. 2002 The deep-water coral *Lophelia pertusa* in Norwegian waters: distribution and fishery impacts. *Hydrobiologia* **471**, 1–12.

FSBI 2001 *Marine protected areas in the North Sea, briefing paper 1*. Cambridge: Fisheries Society of the British Isles.

Gell, F. R. & Roberts, C. M. 2003*a* *The fishery effects of marine reserves and fishery closures*. Washington, DC: WWF-US. See http://www.worldwildlife.org/oceans/fishery_effects.pdf

Gell, F. R. & Roberts, C. M. 2003*b* Benefits beyond boundaries: the fishery effects of marine reserves. *Trends Ecol. Evol.* **18**, 148–155.

Grantham, B. A., Eckert, G. L. & Shanks, A. L. 2003 Dispersal potential of marine invertebrates in diverse habitats. *Ecol. Appl.* **13**, S108–S116.

Grattan-Cooper, A. 1996 Untitled. *Sanctuary* **25**, 10.

Grift, R. E., Rijnsdorp, A. D., Barot, S., Heino, M. & Dieckmann, U. 2003 Fisheries-induced trends in reaction norms for maturation in North Sea plaice. *Mar. Ecol. Prog. Ser.* **257**, 247–257.

Hall-Spencer, J., Allain, V. & Fosså, J. H. 2001 Trawling damage to northeast Atlantic ancient coral reefs. *Proc. R. Soc. Lond. B* **269**, 507–511. (doi:10.1098/rspb.2001.1910)

Hall-Spencer, J. M. & Moore, P. G. 2000 Scallop dredging has profound, long-term impacts on maerl habitats. *ICES J. Mar. Sci.* **57**, 1407–1415.

Halpern, B. 2003 The impact of marine reserves: do reserves work and does size matter? *Ecol. Appl.* **13**, S117–S137.

Hastings, A. & Botsford, L. W. 2003 Comparing designs of marine reserves for fisheries and for biodiversity. *Ecol. Applic.* **13**, S65–S70.

Horwood, J. W., Nichols, J. H. & Milligan, S. 1998 Evaluation of closed areas for fish stock conservation. *J. Appl. Ecol.* **35**, 893–903.

Hutchings, J. A. 2000 Collapse and recovery of marine fishes. *Nature* **406**, 882–885.

Jackson, J. B. C.(and 18 others) 2001 Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**, 629–638.

Johnstone, J. 1905 *British fisheries: their administration and their problems*. London: Williams & Norgate.

Kaiser, M. J. 2003 Are closed areas the solution? *Mar. Conserv.* **5**, 11.

Kaiser, M. J., Spence, F. E. & Hart, P. J. B. 2000 Fishing-gear restrictions and conservation of benthic habitat complexity. *Conserv. Biol.* **14**, 1512–1525.

Kramer, D. L. & Chapman, M. R. 1999 Implications of fish home range size and relocation for marine reserve function. *Environ. Biol. Fish.* **55**, 65–79.

Link, J. S. & Demarest, C. 2003 Trawl hangs, baby fish, and closed areas: a win-win scenario. *ICES J. Mar. Sci.* **60**, 930–938.

McIntosh, W. C. 1899 *The resources of the sea*. London: Clay and Sons.

Mora, C. & Sale, P. F. 2002 Are populations of coral reef fish open or closed? *Trends Ecol. Evol.* **17**, 422–428.

Morgan, L. E. & Chuenpagdee, R. 2003 *Shifting gears: addressing the collateral impacts of fishing methods in US waters*. Washington, DC: Island Press.

Murawski, S. A., Brown, R., Kai, H.-L., Rago, P. J. & Hendrickson, L. 2000 Large-scale closed areas as a fisheries management tool in temperate marine systems: the Georges Bank experience. *Bull. Mar. Sci.* **66**, 775–798.

Murray, S. N.(and 18 others) 1999 No-take reserve networks: sustaining fishery populations and marine ecosystems. *Fisheries* **24**, 11–25.

Myers, R. A. & Worm, B. 2003 Rapid worldwide depletion of predatory fish communities. *Nature* **423**, 280–283.

New England Fishery Management Council 2004 Final Amendment 10. Atlantic sea scallop fishery management plan. See http://www.nefmc.org/scallops/planamen/a10/final_amend_10.htm.

NEFSC (Northeast Fisheries Science Center) 2001 Assessment of 19 northeast groundfish stocks through 2000. A report to the New England Fishery Management Council's Multi-Species Monitoring Committee. Northeast Fisheries Science Center reference document 01-20. See http://www.nefsc.noaa.gov/nefsc/publications/crd/crd0120/

Norse, E. A., Crowder L. B., Gjerde K., Hyrenbach D., Roberts C., Safina C. & Soulé M. E. 2005 Place-based ecosystem management in the open ocean. Chapter 18 in *Marine Conservation Biology* (ed. E. A. Norse & L. B. Crowder). Washington: Island Press. (In the press.)

N.R.C. (National Research Council) 2002 *Effects of trawling and dredging on seafloor habitat*. Washington, DC: National Academy Press.

Okey, T. A. 2003 Membership of the eight Regional Fishery Management Councils in the United States: are special interests over-represented? *Mar. Pol.* **27**, 193–206.

Pastoors, M. A., Rijnsdorp, A. D. & Van Beek, F. A. 2000 Effects of a partially closed area in the North Sea ('plaice box') on stock development of plaice. *ICES J. Mar. Sci.* **57**, 1014–1022.

Recchia, C., Farady, S., Sobel, J. & Cinner, J. 2003 *Marine and coastal protected areas in the United States Gulf of Maine region*. Washington, DC: The Ocean Conservancy.

Roberts, C. M. 2002 Deep impact: the rising toll of fishing in the deep sea. *Trends Ecol. Evol.* **17**, 242–245.

Roberts, C. M. 2003 Our shifting perspectives on the oceans. *Oryx* **37**, 166–177.

Roberts, C. M. & Hawkins, J. P. 1997 How small can a marine reserve be and still be effective? *Coral Reefs* **16**, 150.

Roberts, C. M. & Hawkins, J. P. 1999 Extinction risk in the sea. *Trends Ecol. Evol.* **14**, 241–246.

Roberts, C. M. & Hawkins, J. P. 2000 *Fully-protected marine reserves: a guide*. Washington, DC and University of York, UK: WWF Endangered Seas Campaign. See www.panda.org/resources/publications/water/mpreserves/mar_dwnld.htm

Roberts, C. M. & Sargant, H. 2002 Fishery benefits of fully protected marine reserves: why habitat and behaviour are important. *Natural Resource Model.* **15**, 487–507.

Roberts, C. M.(and 13 others) 2003*a* Ecological criteria for evaluating candidate sites for marine reserves. *Ecol. Appl.* **13**, S199–S214.

Roberts, C. M.(and 11 others) 2003*b* Application of ecological criteria in selecting marine reserves and developing reserve networks. *Ecol. Appl.* **13**, S215–S228.

Rodwell, L. D. & Roberts, C. M. 2004 Fishing and the impact of marine reserves in a variable environment. *Can. J. Fish. Aquat. Sci.* (In the press.)

Rodwell, L. D., Barbier, E. B., Roberts, C. M. & McClanahan, T. R. 2002 A model of tropical marine reserve-fishery linkages. *Natural Resource Model.* **15**, 453–486.

Rose, G. A. & O'Driscoll, R. L. 2002 Capelin are good for cod: can the northern stock rebuild without them? *ICES J. Mar. Sci.* **59**, 1018–1026.

Russ, G. R. 2002 Yet another review of marine reserves as reef fishery management tools. In *Coral reef fishes. Dynamics and diversity in a complex ecosystem* (ed. P. F. Sale), pp. 421–443. San Diego, CA: Academic Press.

Sadovy, Y. 1996 Reproduction of reef fishery species. In *Reef fisheries* (ed. N. V. C. Polunin & C. M. Roberts), pp. 15–60. London: Chapman & Hall.

Shanks, A., Grantham, B. A. & Carr, M. H. 2003 Propagule dispersal distance and the size and spacing of marine reserves. *Ecol. Appl.* **13**, S159–S169.

Sladek Nowlis, J. S. & Roberts, C. M. 1999 Fisheries benefits and optimal design of marine reserves. *Fish. Bull.* **97**, 604–616.

Stokes, K. & Law, R. 2000 Fishing as an evolutionary force. *Mar. Ecol. Prog. Ser.* **208**, 307–309.
Trexler, J. & Travis, J. 2000 Can marine protected areas conserve and restore stock attributes of reef fishes? *Bull. Mar. Sci.* **66**, 853–873.
Turpie, J. K., Beckley, L. E. & Katua, S. M. 2000 Biogeography and the selection of priority areas for conservation of South African coastal fishes. *Biol. Conserv.* **92**, 59–72.
Watson, R. & Pauly, D. 2001 Systematic distortions in world fisheries catch trends. *Nature* **414**, 534–536.